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The dense energy deposition from a low-energy nuclear recoil produces, via the thermoacoustic effect, a brief yet intense pressure pulse that can be used for WIMP or neutrino detection in some fiber-optic devices sensitive to acoustooptic disturbances. Several possible detection schemes are described: all of them are inspired by modern fiber-optic sensor technologies and share common characteristics of low-cost and expected insensitivity to minimum-ionizing backgrounds.

The detection of low-energy nuclear recoils originating in neutrino or Weakly Interacting Massive Particle (WIMP) elastic scattering off nuclei has been the subject of a great experimental effort in the last two decades. The difficulties involved in the development of detectors adequate for this task are multiple: *i*) the signal rate expected is generally very low (few counts per kg target per day or much less), imposing the need for large (multi-kg) detector masses, *ii*) the signal accumulates in the keV or sub-keV region, requiring a low energy threshold, *iii*) the recoil signal must be extruded from a sea of dominant backgrounds, most of them originating in minimum-ionizing particles. The interest in this particular area of detector development is amply justified: WIMPs constitute one of the best candidates for Dark Matter at the galactic level [1]. Numerous ongoing and planned searches aim at the detection of WIMP-induced recoils [2], employing a variety of techniques. Some of the most sensitive present WIMP detectors rely on costly and cumbersome cryogenic techniques. Unfortunately, some theoretically well-motivated WIMP candidates such as those arising from supersymmetric extensions of the Standard Model can have elastic scattering cross sections so small that only ton or multi-ton background-insensitive devices have a realistic chance at their direct detection. Low-cost and simplicity become in this way a determinant factor in the design of next-generation WIMP detectors.

A second important objective for these devices is the detection of *coherent* neutrino scattering: an uncontroversial process in the Standard Model, the scattering off nuclei of low-energy neutrinos ($< \text{few tens of MeV}$) via the neutral current [3] remains undetected. The long neutrino wavelength probes the entire nucleus, giving rise to a large coherent enhancement in the cross section, roughly proportional to neutron number squared [4]. A quantum-mechanical condition for the appearance of coherent effects is the indistinguishability of initial and final states and hence the absence of a charged-current equivalent. In principle, it would be possible to speak of *portable* neutrino detectors since the expected rates can be as high as several hundred recoils/kg/day (Fig. 1), by

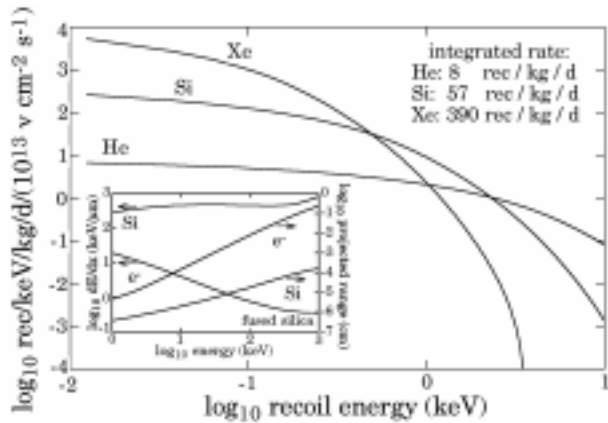


FIG. 1. Nuclear recoil energy spectrum from neutral-current scattering of reactor neutrinos on different targets. *Inset*: stopping power and range of low-energy Si recoils and electrons in fused silica (SiO_2).

no means a “rare-event” situation. A detector of this type would open the door to extraordinary applications in “neutrino technology” [5,6] (planetary tomography and prospecting, telecommunications, extra-galactic neutrino detection and strategic applications). However, the recoil energy transferred to the target is of a few keV at most for the lightest nuclei (Fig. 1): several ambitious proposals to use new-generation cryogenic detectors [4,7,8] have been put forward, but *no existing device* meets the target mass and energy threshold requirements involved in this measurement. The interest in observing this process is not purely academic nor the stuff of science-fiction. For instance, a neutral-current detector responds the same way to all known neutrino types, meaning that the observation of neutrino oscillations in such a device would be direct evidence for a fourth sterile neutrino. These must be invoked if all recently observed neutrino anomalies are accepted at face value [9] and may play an important role as Dark Matter [10]. Separately, the cross section for this process is critically dependent on neutrino magnetic moment: concordance with the Standard Model prediction would *per se* largely improve the present experimental sensitivity to μ_ν [11]. Finally, this mechanism plays a most important role in neutrino dynamics in supernovae and neutron stars [3], adding to the attraction of a laboratory measurement.

The research project described next has as its goal the development of cost-effective cryogenic-free detector technologies responsive to these low-energy recoils while being insensitive to competing backgrounds. The innovative approach proposed profits from the enormous ongoing progress in optoelectronic components and devices, making use of inexpensive telecom-grade optical fibers, light sensors and amplifiers.

At the microscopic level (nm scale) a nuclear recoil is an extremely violent event. The scenario, common to other forms of high-LET particle interaction, starts with the formation of a highly-ionized plasma in the recoil aftertrack: for sufficiently dense energy depositions the nuclear and electronic temperatures can reach local values in the thousands of degrees Kelvin. This transient ($\sim 10^{-12}$ s) heat pulse or “hot-spike” [12] is soon quenched: the rapid adiabatic expansion of the material provokes a considerable shock wave (the “thermoacoustic” effect [13]), reaching local peak pressures in excess of 10^5 atm [14] that take away a large fraction of the deposited energy in the form of phonons. This acoustic shock-wave has been used before as a monitoring method for intense beams of minimum-ionizing radiation [15,16] and can play a role in radiation damage to tissue [14]. The frequency of the dominant sound emission is $\sim c_s/l$ (c_s is the sound speed, l is the transverse track size), which for keV energy recoils, having a comparable l and range (Fig. 1, inset), is in the tens or hundreds of GHz. This is unfortunate, since such frequencies are rapidly damped in most room-temperature materials over distances of the order of few microns [14,16]. This limitation is bypassed in a proposal to use Si crystal bolometers, where ballistic phonons can propagate and be detected over macroscopic (cm) distances at cryogenic temperatures [7]. While derivatives of this approach have found successful applications in WIMP searches [17], the feasibility of scaling it up to the large target masses required for the ultimate WIMP detector remains an open question. These bolometers currently display effective energy thresholds still far too high for coherent neutrino detection, with no immediate improvement in sight.

The central question is then: can a brief (\sim ns) yet intense pressure pulse propagating over a short ($\sim \mu$ m) distance in an room-temperature device be used for efficient nuclear recoil detection? This proposal intends to show that for some unsophisticated contraptions the answer may be “yes”.

A brief exercise in mental gymnastics provides a first approach: take the O(kg) target mass, elongate it until its geometrical cross section becomes comparable to the size of the recoil-induced disturbance and send a probe through it, one able to carry the fleeting information of this short-lived event to a monitoring instrument down the line. To envision a fiber-optic device, where the transmitted light is the probe and the fiber itself the target is then only natural. In an era when fiber-optic communications are becoming inexpensive, commonplace and transmission speeds are rapidly approaching the THz barrier, the idea seems timely. What is more, a plethora of fiber-optic sensing devices [18,19] have amply demonstrated the exquisite sensitivity that they provide in a variety of applications.

Fig. 2 (top) illustrates a first example. The strategy depicted there is freely inspired by the “microbend”

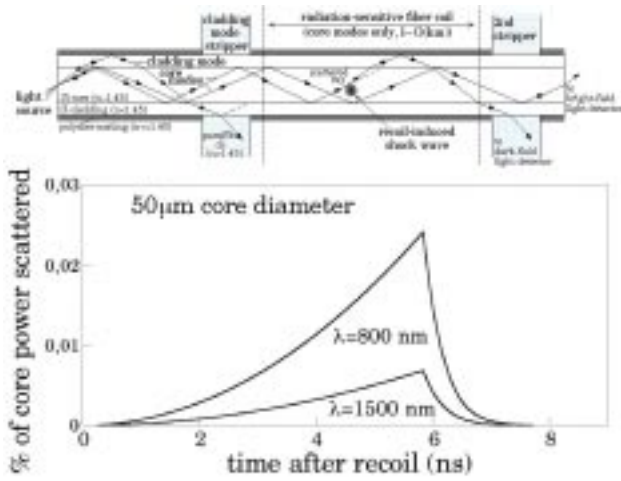


FIG. 2. *Top*: conceptual design of a low-energy recoil detector using HCS telecom fiber. *Bottom*: estimated magnitude of a keV recoil-induced disturbance using Mie scattering theory.

acoustic fiber sensor [19,20]. A common multimode hard-clad silica (“HCS”) fiber, of wide use in industrial control applications presents the interesting property of being a true dual lightguide: injected photons can propagate either through core modes or external higher-order cladding modes (Fig. 2, top). These cladding modes can be completely removed by immersing a short segment of denuded fiber in a high-index of refraction (n) liquid (a so-called “mode stripper”), “cleaning” one of the two possible light paths. While some mixing of core and cladding modes (“mode beating”) can occur down the fiber due to careless winding of the fiber coil, scattering on microbubbles, etc., this separation can be maintained over long distances (a first prototype under construction by the author at Groupe de Physique des Solides displays a leakage of the core-transmitted power to the cladding of $< 3\%$ over a tight 100 m coil). In a microbend acoustic sensor, a special mechanical transducer excited by acoustic pressure can affect the core modes in such a way that they feed light again to the otherwise blank cladding channel (present microbend sensors are sensitive to transducer displacements of less than an Angstrom). This cladding light can then be extracted at the end of the sensing fiber by a second mode stripper and detected, providing a measure of the acoustic signal [20]. Here, the role of the transducer can be played instead by the short-lived changes in density, polarizability and index of refraction expected to accompany a recoil-induced shock-wave (i.e., the well-known “acoustooptical” effect [21,22]), which are able to deflect (even if minimally) some of the core power into higher modes (Fig. 2, top). The duration and intensity of the cladding pulse so produced can be calculated using Mie scattering theory (Fig. 2, bottom) as is generally done to estimate the effect on light attenuation of micron-sized density fluctuations in fibers [23]. The calculation accounts for the magnitude and propagation

of the pressure wave following [14–16], includes its large attenuation at high frequencies [24], uses the index of refraction of shock-compressed fused silica as in [25] and pays attention to the fact that shock-wave and sound speeds are not the same in some regimes [26]. To give the reader a reference point, the $t = 0$ change in n at the recoil site can be as large as $\sim 7\%$. While small, the signal expected from this design can in principle be easily detected with fast photodiodes like those now commonly used in optical telecom networks and amplified with low-noise chips like those developed for GHz-band cellular telephony. The first prototype device presently under development is expected to have a sensitivity at least two orders of magnitude better than what is predicted by the Mie estimate (in order to accomplish this, several features such as a low-noise, high-intensity LED light source, selective mode injection [27], careful choice of PIN plus amplifier, and a 4π cladding light collector are being implemented).

Several remarks are in order: the bandwidth and attenuation properties of the fiber must allow for this brief signal to propagate over the long fiber distances needed to ensure a large-mass recoil detector. The excellent quality of modern telecom fiber guarantees this. For the same reason (substantial target mass), only large core-diameter ($\geq 100\ \mu\text{m}$) multimode fibers seem to be of interest for the goal in mind. Specialty fiber (polarization-preserving, single-mode, etc.) defeats the purpose by being not only much more expensive but having an insufficient mass-to-length ratio. Most importantly, the devices envisioned are expected to be largely insensitive to isolated minimum-ionizing radiation, the reason being the large dependence of the magnitude of the thermoacoustic pressure spike on particle stopping power [14–16]: the sparse energy deposition typical of low-LET particles (Fig. 1, inset) is expected to produce no measurable effect. The fact that the fused silica used in commercial fibers is of low intrinsic U and Th-chain radioactivity is of special mention: even small concentrations of metal impurities are known to jeopardize light transmission and hence a special industrial process of silica preform purification is followed. Therefore, a very low rate of events arising from alpha-recoils or fission fragments in the fiber material is anticipated.

Many of the principles used in other fiber-optic sensors can be adapted for the detection of WIMP or neutrino recoils. For instance, another possibility is the use of a Sagnac interferometer [18,28], a design widely adopted in commercial fiber-optic gyroscopes for its simplicity and robustness vis-a-vis external disruptions (temperature gradients, sound, etc.). A more in-detail look at the interaction process described above would show that the shock-wave must produce a strong iridescence effect on the light it intersects, due to the comparable photon wavelength and shock-train spatial width. The effect of this phase shift on a Sagnac sensing loop (which

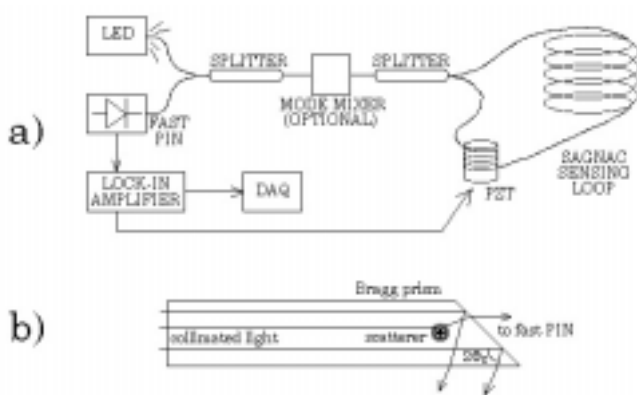


FIG. 3. *a)* A minimal-configuration Sagnac fiber optic interferometer using multimode fiber. *b)* Can the combination of a Bragg prism and a fast PIN diode be used as a sensitive (dark-field) recoil detector?

can be up to few km long) should be readily measurable, provided that the “gyroscope” is instrumented to look for nanosecond phase changes, which is evidently never the case in normal use. An exception to this statement is found in new ultrafast optical switches such as the Sagnac TOAD [29], which presents a strong parallel to the recoil detection scheme outlined here (the curious reader is encouraged to consult [29]). Interestingly enough, minimum-configuration, low-cost fiber optic gyros can be assembled out of the thick multimode fiber required for recoil detection [30]. Other schemes using polarization measurements and Bragg prisms are under study (Fig. 3). The simultaneous use of multiple photon wavelengths for redundancy and noise rejection can be envisioned (wavelength-selective emitters, sensors and splitters are now common use in telecom).

After a working prototype is achieved, calibration in a variety of neutron fields would be the next natural step. Needless to say, what is good for neutrino recoils is good for the detection of neutrons. Present fiber optic dosimeters are rudimentary [31] in the sense that they offer no real-time detection of single particles. Passive scintillating fibers are an exception, however of no use here for reasons of cost, absorption length (which limits target mass), lack of built-in background discrimination and high energy threshold. Therefore, applications in neutron dosimetry should not be discounted. A challenge will be the extraction of energy information from the devices (even though most of the applications described in the first part of this paper can be pursued with threshold detectors): time-frequency and amplitude analysis of the signals can cast light on this.

In conclusion, the tools necessary for novel low-cost, room-temperature, background-insensitive neutrino and WIMP detectors seem to be up for grabs, thanks to the extraordinary recent developments in the at first sight unrelated fields of telecom, optoelectronics and fiber optic sensors.

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